Numerical Weather Prediction

Assessment of the requirement for 23.6-24.0 GHz observations for weather forecasting

Forecasting Research Technical Report No. 440

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The use of 23.6-24.0 GHz observations in meteorology

There is a long history of the use of ~20-24 GHz observations from space by meteorologists. After a series of research satellites the first operational satellite was the Special Sensor Microwave Imager, flown by the US Navy. We have had continuous data from SSM/I since 1987. However due to restrictions on the use of military satellite data it has only been used operationally by Met Centres since the late 1990s.
The first civilian satellite to observe at 23.6-24.0 GHz was the Advanced Microwave Sounding Unit, first launched on the NOAA KLM series in May 1998. This has been used operationally by the Met Office since March 1999. This specific channel is included on ***all*** planned future polar orbiting satellite sounding missions including METOP, the new US Navy instrument SSMIS, which replaces SSM/I and the future NOAA series known as NPOESS.

Characteristics of 23.6-24.0 GHz for NWP and why its unique

A channel at or near the 22.235 GHz water vapour line is important as it is the only method currently available to gain low level humidity information globally in the presence of clouds. The wavelength is sufficiently long for most clouds to be transparent. Furthermore at 31 GHz the observations become much less sensitive to water vapour but much more sensitive to cloud liquid water. At 18 GHz the observations have a low sensitivity to water vapour and cloud and are therefore mostly sensitive to the earth's surface.

Initially different instruments chose different frequencies close to the water vapour line at 22.225 GHz. However all future instruments are converging on 23.6-24.0 GHz. The reasons for this are both scientific and technical. Scientifically the bands in the wing of the line have a higher information content for total water vapour than a band centred on the spectral line (22.21-22.5 GHz) largely because of a lower sensitivity to vertical structure in the water vapour profile. Technically the band on the high frequency side of the line is better than 21.2-21.4 GHz because the lower frequency band already shares with active services and has only 200 MHz bandwidth compared to 400 MHz at 23.6-24.0 GHz. For these reasons the EESS community have converged on 23.6-24.0 GHz band. Note that in this paper for absolute clarity we shall always refer specifically to the band (e.g. 23.6-24.0 GHz) when referring to bands near 24 GHz whereas for other bands for brevity we shall simply refer to the nearest frequency, since those bands are not the specific topic under discussion.

However it's important to realise all three channels are sensitive to all three things (water vapour, cloud, surface) to differing degrees. The use of these three frequencies (18, 23.6-24.0 and 31 GHz) together is a unique resource for simultaneously observing water vapour, clouds and the surface. The word unique here is not an exaggeration. There is no other electromagnetic band where this is possible. If only 2 of the channels are present it is not sufficient to separate the effect of water vapour, clouds and surface on the two measurements. Therefore if we lose one out of three we lose not one of the parameters but potentially all three. For the surface this is less true and systems without 18 GHz can still give good information on water vapour and cloud. However the individual contributions of 23.6-24.0 and 31 GHz are absolutely necessary. So for water vapour and cloud retrievals and analysis the loss of 23.6-24.0 GHz makes both parameters impossible to retrieve. Figure 1 compares absorption from water vapour, cloud liquid water and oxygen as a function of frequency. The ratio of absorption by cloud and vapour at 18 and 31 is rather similar which makes this pair of channels relatively ineffective at separating cloud from water vapour in the analysis. By contrast the water vapour absorption at 23.6-24.0 is five times stronger than cloud absorption which makes the pair of channels (23.6-24.0 and 31 GHz) extremely effective at separating water vapour from cloud liquid water. Whilst the absolute level of water vapour and cloud absorption at one frequency depend on the choice of profile the ratio between two frequencies is only weakly sensitive to choice of profile, so this is a robust result.

In order to use moisture observations effectively NWP systems must first get the dynamics right. In the past 5-10 years an improved data assimilation system coupled with a better dynamical core to the model and the vast increases in available satellite data have indeed improved the Met Office model's dynamical fields. Increasing positive impact is being found from assimilating moisture observations. Research is well underway on using cloud liquid water information directly. In 1996 HIRS moisture sensitive radiances gave a significant improvement in NWP performance (Renshaw et al. 1997). A similar improvement was seen in 2001 when AMSU-B data was used for the first time (English et al. 2000). In 2003 AMSU-B data was used for the first time in the UK mesoscale model (English et al. 2003). Assimilation of SSM/I water vapour information derived from 24 GHz is now showing positive impact (Bell, pers. comm.).

However there is one further and important impact of 23.6-24.0 GHz observations on NWP which is more important than the direct sensitivity. The cloud liquid water information allows us to determine when the

temperature sounding channels of AMSU-A are unaffected by cloud liquid water. This is critical for the use of the lower tropospheric temperature sounding channels. The impact of the AMSU temperature sounding channels is very important to NWP. In the southern hemisphere the performance of NWP without AMSU data has minimal skill, as there are so few other observations. The impact of losing AMSU is also very large in the tropics. In the northern hemisphere there are other observations, but the skill of the forecast without AMSU is still seriously degraded, but would retain significant skill. However users of the northern hemisphere NWP products would probably have to accept a step back to mid-1990s levels of skill. In the southern hemisphere and tropics the "step back" without AMSU would be considerably larger. Not all impact would be lost if 23.6-24.0 GHz was lost but a major hit on performance would be inevitable.

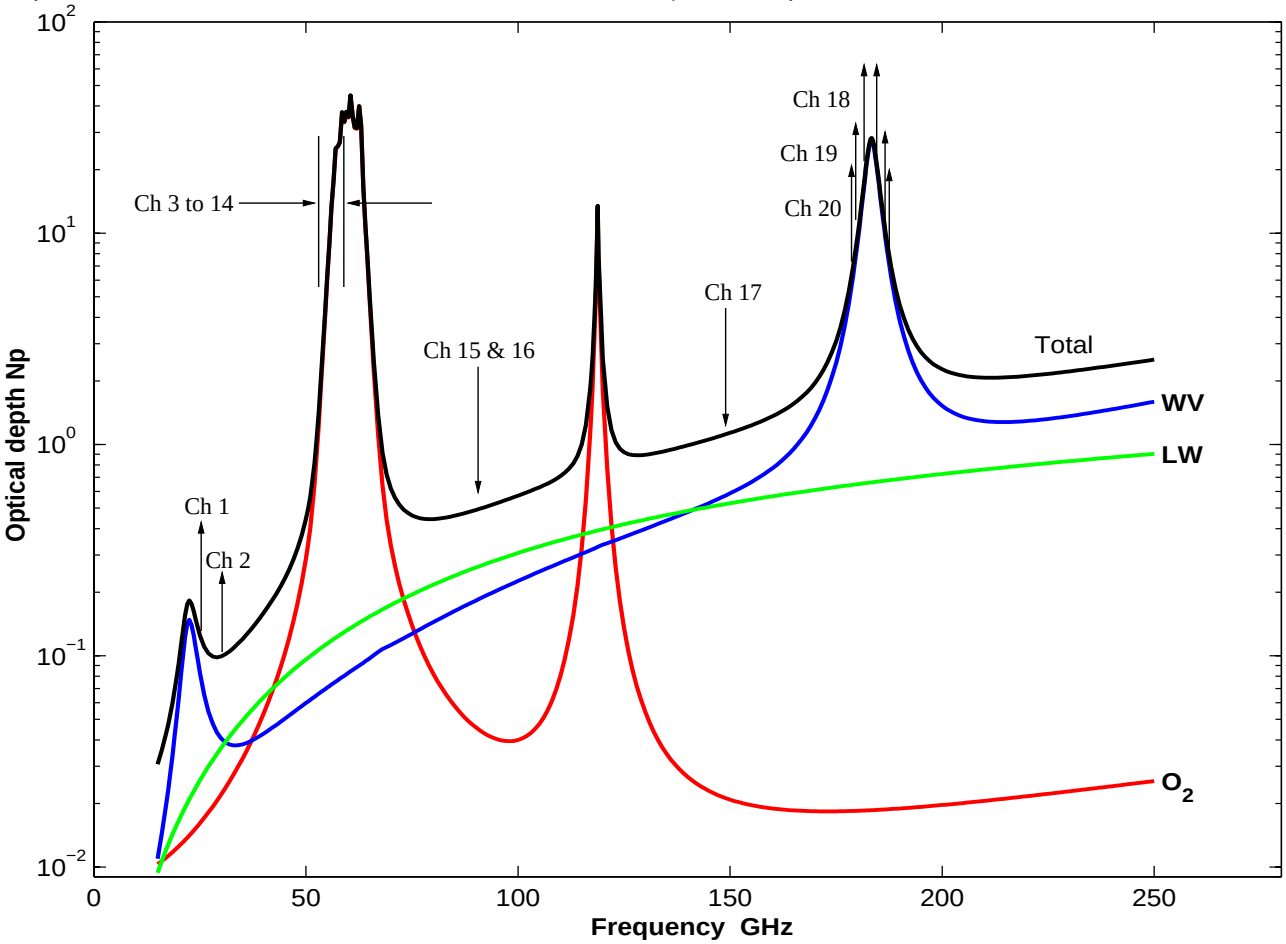

Figure 1: Comparison of total atmospheric optical depth due to water vapour, liquid water and oxygen for 200 gm^{-2} cloud and US Standard Atmosphere.

Use of 23.6-24.0 GHz over land

The primary value and use of satellite data is usually considered to be over the sea. It is true that satellite data impact is largest in data sparse areas, of which the oceans are an obvious example. It is also true that interpretation of satellite measurements is easiest if the surface is a flat and fairly homogeneous, a description more readily associated with ocean than land. For this reason NWP centres have rightly focused initial exploitation of 23.6-24.0 GHz (and all other satellite sounding data) over the oceans and in the upper troposphere and stratosphere, where the surface type is unimportant. This has been used by the car industry as suggesting 23.6-24.0 GHz data is of less value over land than ocean. It is undeniably correct that use of 23.6-24.0 GHz over land is difficult. The land surface variability has to be well characterised, and if there is no thermal contrast between surface emission and atmospheric temperature the 23.6-24.0 GHz information content becomes quite low. However modern data assimilation systems can handle non-linear relationships between observations and geophysical variables. Therefore it does not matter that sometimes the information content is low – the data assimilation system will use the data effectively when the information content is high. English (1999) showed that if the emissivity of the surface is significantly less than 1 and emissivity is known better than 1% humidity analysis from 23.6-24.0 GHz is possible over land. But more importantly the combined use of 23.6-24.0 and 31 GHz can provide very accurate cloud liquid water information if the surface emissivity is only slightly less than 1. This has been independently demonstrated in a paper by Prigent (1997) in Journal Geophysical Research, who showed that cloud liquid water information could be analysed over many land surfaces. Furthermore numerous authors have

demonstrated that these channels contribute to precipitation retrieval over land (a list is given in English 1999). The car industry is right to argue that humidity analysis from 23.6-24.0 GHz over land is as severely limited by other problems as by potential RFI from car radars (although other issues may be scientifically solvable, RFI is not). However the use of 23.6-24.0 GHz for cloud and rainfall screening of AMSU temperature sounding is as important over land as over the ocean. This point is ignored by the car industry, either on purpose or because they do not understand it.

English (1999) show the potential to gain information over land in an idealised situation, but say nothing about real uncertainty in land surface emissivity modelling nor actual variability. To gain some insight into this the difference between modelled brightness temperatures and observed brightness temperatures (the innovation) has been compared for land and sea points. When radio frequency interference (RFI) is greater than $1/10^{th}$ of the innovation it is considered to be significant (i.e. likely to cause misinterpretation of the innovation). Therefore we want to know how often at a given threshold (say 0.2 K) $1/10^{th}$ of the innovation is less than the threshold. This will tell us how often RFI at that level would be significant. In Figure 2 the percentage of points is plotted where the $1/10^{th}$ of the innovation is less than the threshold on the x-axis. It is remarkable that the curves for sea and land points are very similar. For example for sea points 32% of points fall below 0.2 K. That is to say RFI of 0.2 K would exceed 10% of the innovation 32% of the time. Remarkably for land points the RFI tolerance is actually lower than for sea points, not higher as might have been expected. 38% of the land points fall below 0.20 K. That is to say RFI of 0.20 K would exceed 10% of the innovation vector 38% of the time. What this shows is that we are more sensitive to RFI over land than might be expected from casual but incorrect suggestions that land surface emissivity is less well known and more variable than ocean surface emissivity. To reduce significant interference to occur less than 5% of the time over land would require a threshold of 0.03 K.

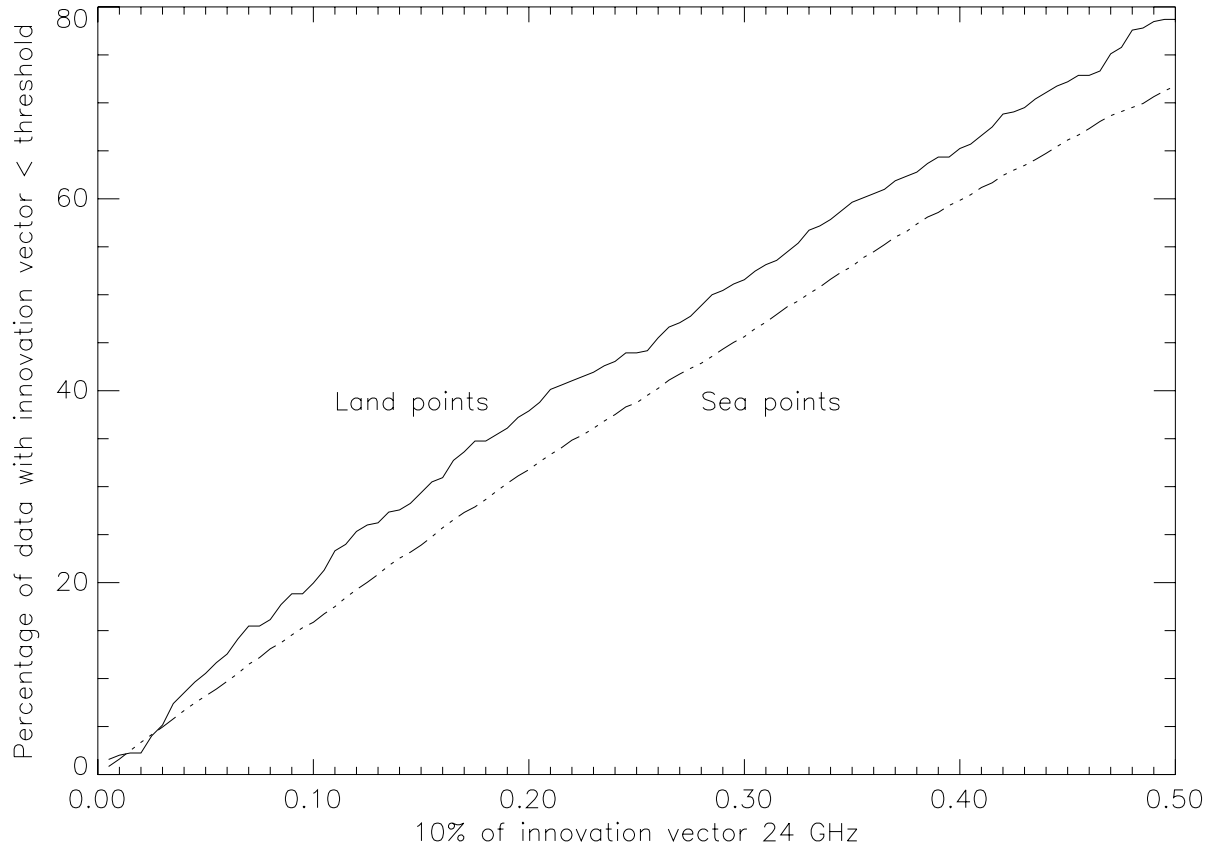

Figure 2: Histogram of the occurrence of $1/10^{th}$ of the innovation vector (the 24 GHz element only) being less than the threshold defined by the x-axis which is innovation in K.

The reason for the higher sensitivity over land is believed to be due to lower variability. We can model the variations of ocean emissivity remarkably well, but as these variations are so large errors of 1-2% in emissivity reflect a high degree of accuracy in the model. For land emissivity with the exception of snow cover and actual surface water (as opposed to soil moisture) there is very little variation in emissivity, and

therefore although it may be poorly modelled the actual errors scale with the variability. It is for this reason that sensitivity to RFI over land is high.

The precipitation potential is also used in imagery in support of mesoscale models (UK, Europe, Iraq). A project is currently being funded through the Met Support Group extending the range and capability of these imagery products from AMSU both the European and Crisis Area Mesoscale Models.

Impact of loss of 23.6-24.0 GHz on NWP

For the reasons discussed above the largest impact of the loss of 23.6-24.0 GHz over land would be to reduce the amount of AMSU used for temperature sounding. The value of AMSU for temperature sounding over land at low levels was first demonstrated over Siberia, where data was switched on with strong quality control using 23.6-24.0 GHz prior to the year 2000, because it was anticipated that loss of radiosondes over Siberia due to the millennium bug was possible and beyond our control. Therefore extra use of the satellite data was a mitigation against this loss. Surprisingly, at the time, it was found that the data provided significant additional skill to forecasts even when the radiosondes were present (English, Poulsen and Renshaw 1999). So the data was switched on before December 31st 1999, rather than waiting for a critical loss of radiosonde data (which, in fact, did not happen). Having demonstrated that the data was important to use a significant fraction of the Met Office R&D effort in satellite data processing has been directed at improved use of AMSU data over land. These efforts will have been wasted if we lose 23.6-24.0 GHz. As stated earlier all future sounding systems have a 23.6-24.0 GHz channel as a critical part of the system design. So the Met Office has invested through EUMETSAT and METOP heavily both in the hardware, scientific research and development and operational code development for exploitation of this capability. Full exploitation has not yet been achieved but the role of 23.6-24.0 GHz in satellite data processing is well established.

Evaluation of EESS and SARA (car industry) positions

As small levels of RFI are hard to detect low levels of emission are dangerous. We may think we are OK, but be misinterpreting RFI as atmospheric variations. The so called “innovations” which are the small changes to the analysis made by observations in each assimilation cycle are less than 0.2 K 5 % of the time. The largest values however exceed 10 K. Therefore unless RFI is over 10 K it can not be distinguished from natural variability. We can not therefore simply exclude contaminated data. If contamination is occurring at a level likely to give innovations greater than 0.2 K we can’t use the data. Figure 2 could be used to support an even tighter figure and 0.03 K would not be a scientifically unreasonable position. The only safe level of emission is zero, and this should be the ideal position. EESS has agreed primary protection in this band. However studies do agree that a market share (assuming a static level of car use) of 5.9% would be unlikely to exceed the agreed levels of protection required for meteorological exploitation of the band. Therefore the EESS community has campaigned for this figure (the car lobby wanted 8.9%). The EESS community has also lobbied for an agreed transition to 79 GHz (a frequency used by nobody, and actually better for the car radar application, but slightly more expensive to develop and with a longer lead time, because 24 GHz devices already exist because of the wide use of this frequency in existing applications). The Japanese car industry for example is developing devices at 79 GHz. The EESS community have also lobbied for automatic deactivation of devices. I believe the compromise position of EESS is a position which has a strong scientific basis and which would minimise the impact of these devices on meteorology, although it falls short of the absolute protection we ideally need.

Conclusion

The conclusion is to support the internationally agreed EESS position, but remind the authorities that our ideal position would still be absolute protection.

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